TID-24996

SAFETY OF UNDERGROUND NUCLEAR TESTING

SUMMARY REPORT ON ACTIVITIES FOR ASSURING THE SAFETY OF UNDERGROUND NUCLEAR TESTING

April 1969

UNITED STATES ATOMIC ENERGY COMMISSION
NEVADA OPERATIONS OFFICE

FOREWORD

Public safety associated with underground nuclear testing is of paramount concern to the Atomic Energy Commission. Specific potential problems have been identified and during almost 25 years of testing have received close attention. As the yields of underground events have increased, increasing attention has been given to those effects which are related to the larger tests.

The Commission is aware that various groups have indicated increased interest in the seismic and other environmental effects associated with these testing activities. This paper evaluates the Commission's understanding of the effects of underground nuclear tests, explains what is being done to prevent those effects from becoming hazards, and describes actions which are underway to develop a clearer insight of the problems involved. The Atomic Energy Commission in collaboration with representatives of the three nuclear weapon laboratories—Los Alamos Scientific Laboratory, Lawrence Radiation Laboratory, and Sandia Laboratories—has prepared the attached report.

In explaining their subjects, the authors have tried to avoid scientific jargon and, within the limits of the security, have provided that descriptive scientific and technical information they considered necessary to explain their subjects.

The reader interested in learning more about a particular subject will find a selected supplemental reading list appended.

TABLE OF CONTENTS

INTRODUCTION

For the compelling reasons of national security, the Atomic Energy Commission (AEC) conducts underground nuclear weapons tests. Most of the tests take place at the Nevada Test Site (NTS) in southern Nevada. Recently, tests of a little over one megaton have taken place at NTS. While higher-yield tests will be necessary, none will be fired at yields higher than are required to meet the needs of our national security. Depending upon yield, some in the same general yield range may be fired at the NTS; others of greater yields at the supplemental test sites in Central Nevada and on the Aleutian Island of Amchitka, Alaska.

Several different techniques are used for emplacing nuclear test weapons so that the explosions will be contained. The simplest method is to emplace the test device at the bottom of a vertical drilled hole which, in some cases, is lined with steel casing cemented to the hole walls. Another technique is to emplace a test device within a tunnel that has been mined horizontally into a mountainside. With both methods, certain pipes and cables may lead from the emplacement location to the surface as necessary to accommodate the experiments involved. The test emplacements are shut off or "stemmed" with materials and devices appropriate to the configuration of the hole or tunnel being used. Typically a vertical hole might be stemmed from above the point of emplacement to the surface with sand, gravel, and one or more poured concrete plugs. A tunnel might be stemmed with sand and poured concrete plus one or more mechanical closures such as concrete plugs and doors. The reader should be aware that these different emplacement techniques are used and that each is needed to accommodate specific experimental work.

The Commission takes every reasonable precaution to insure that the tests cause no injury to people, either directly or indirectly, and cause no material damage either to the ecology or to man-made structures. In addition, the tests are designed and executed so as to comply with the limited test ban treaty. The precautionary measures are based on extensive studies of the effects of underground explosions. These studies, conducted by the Commission and its contractors and by others in the scientific community, encompass containment and release of radioactivity, ground motion and its effect on structures, aftershocks and earthquake triggering, and radioactive contamination of groundwater. Although man's knowledge of these effects is not complete, the conservative precautionary measures which accompany every test have been successful.

The purpose of this report is to summarize our knowledge of the effects of underground explosions, to describe the safety procedures that are followed, and to outline how the Atomic Energy Commission and the scientific community interact and cooperate in extending our knowledge of the effects of underground explosions.

SUMMARY:

1. Containment and venting are reasonably well understood. A very substantial amount of data is in hand on the containment of nuclear explosions over a broad range of yields. Scaling laws have been developed whereby the depth of burial required to contain an underground explosion of yields in the ranges of interest can be calculated with a high degree of confidence. Test emplacement practices that are used today assure comfortable margins of containment safety; for intermediate and high-yield tests there has been no radioactive leakage.

2. Groundwater conditions have been studied extensively for areas surrounding underground test locations. By geologic and hydrologic exploration, detonation sites are selected to avoid faults and to avoid areas that show unfavorably high permeability or water level gradient. Through these precautions there is a high degree of confidence that radionuclides released from underground nuclear explosions and transported by underground water do not constitute a hazard.

3. The gross characteristics of ground motion caused *directly* by underground nuclear explosions can be predicted with confidence based on yield, distance from the burst point and local conditions. Such prediction, based on empirical data, is sufficient to insure that man-made structures, such as buildings and dams, do not sustain structural damage.

4. Aftershocks which often follow nuclear explosions are generally limited to the vicinity of the burst point. The seismic energy contained in the aftershock earthquake in every case has been much smaller than that of the nuclear explosion. In fact, there is no evidence that the aftershock earthquakes which follow a nuclear explosion could be of energy equal to or greater than that of the nuclear explosion itself, nor is there any experimental basis for predicting that a large-yield test explosion might induce a large and possibly damaging earthquake, either immediately or at a later date. Even so there is concern on the part of some earthquake experts that there is no basis for eliminating the possibility that serious earthquakes might be induced by larger-yield nuclear tests. This is an area in which further study is necessary. Considerable work has been done and will continue to be done in this area with the cooperation and help of seismologists and geophysicists.

5. While there are some differences of scientific opinion about the causes of tsunamis (tidal waves), it is generally accepted that some are created through permanent vertical, ocean-floor displacements that are associated with natural earthquakes. Known experience from earthquakes that may have caused tsunamis plus experience from past underground nuclear events has been examined along with calculated information. Based upon consideration of this experience and information, the chance of the proposed Amchitka tests generating a dangerous tsunami through a triggered earthquake appears to be negligible. It has also been postulated that tsunamis might be caused directly by coupling of energy from the ground wave to the water or indirectly through test caused landslides or underwater slides. For Amchitka these phenomena also appear highly improbable.

6. Safety begins during the design of a nuclear device at the weapon laboratory and includes review and consideration at several levels between the laboratory and the Atomic Energy Commission. Through a very careful and deliberate management process details about the device to be tested and about the device test emplacement along with the comprehensive plan for conducting that test are examined from the standpoint of safety. Only after thorough consideration of these matters are the plans for a specific test approved for execution, with general approval for all tests coming from the President and final specific approval from the Atomic Energy Commission. Finally, there are thorough and redundant operational checks to provide the necessary high confidence that each test can be executed without creating problems of safety.

UNDERGROUND PHENOMENOLOGY

A nuclear explosion underground starts a complex series of events that takes place in times ranging from a small fraction of a second to many hours. A firm understanding of what happens in underground explosions and how they can be contained requires that each of these events be understood. The events are discussed in sequence along with theoretical techniques available for understanding and confirmatory experimental measurements that have been made. Figure 1 is a graphical representation of this sequence.

EARLY PHENOMENA

The sequence starts with the detonation of the nuclear explosive. A large amount of energy is produced in a very short time, for example, one tenth of a millionth of a second (Figure 1a). The material in the nuclear device is vaporized and raised to a temperature of several million degrees. A strong shock moves outward from this hot, high-pressure region, delivering energy to the region outside the cavity and vaporizing some of the surrounding earth (Figure 1b). (Calculations show that in common silicate rock vaporization continues out to a radius of about 6 feet for a yield of 1 kiloton. This radius increases as the cube root of the yield.) At this point, one has a cavity whose contents are mainly vaporized rock and whose pressure is in the neighborhood of one million atmospheres. The cavity continues to expand until its pressure drops to a value about equal to the pressure from the weight of the rock overburden, which is roughly 1 pound per square inch (psi) for each foot of burial depth. Expansion of the cavity is completed within a few tenths of a second (Figure 1c). (A 1-kiloton explosion will produce a cavity having a radius of about 50 feet. Like the radius of vaporization, the cavity radius increases as the cube root of the yield of the explosion.) The initial pressure pulse and the expansion of the cavity produce a series of shock waves which move out into the surrounding material. When this shock energy arrives at the surface, the ground "jumps."

The main tools for understanding cavity growth and the attendant shock waves are theoretical hydrodynamic elastic-plastic calculations coupled with measurements made in many nuclear events. The calculations require as input the knowledge of the properties of the vaporized rock gas in the cavity and detailed information concerning the surrounding earth material. By these calculations regions which will vaporize, melt, or fail either by plastic flow or brittle fracture are predicted. If the surrounding materials are carefully described, the calculations agree well with measurements of radial stress profiles, particle velocity, the time of arrival of the shock wave at the surface, and the radial extent of failed material as indicated by the underground postshot cracks. However, calculational results are quite sensitive to some of the material properties such as the detailed pressure-volume relationship and the criteria for plastic and brittle failure. Therefore, if specific phenomenological effects are to be accurately predicted, the geology of the particular site in question must be examined carefully. Under any circumstances, however, one can always answer the important question "Is the overburden sufficient to contain the explosion?" by making conservative assumptions and relying on experience.

LATE PHENOMENA

Once the cavity has stabilized in size, a sequence of events of a quite different nature commences. Rock vapors rapidly condense, leaving water vapor as the main component of the cavity gas (Figure 1c). The cavity gas cools by heat transfer to the surrounding medium. Eventually, after a time which may vary from a few minutes to hours or even days, the cavity pressure falls to a level such that it plus the natural strength of the rock in the cavity roof is no longer sufficient to support the overburden. Then the cavity collapses, rock falls into the cavity, and the remaining water vapor is condensed quickly, reducing the cavity pressure still more (Figure 1d). Collapse, once started, proceeds upward and forms a chimney in a few seconds. Cavity col-

CAVITY-CHIMNEY FORMATION HISTORY

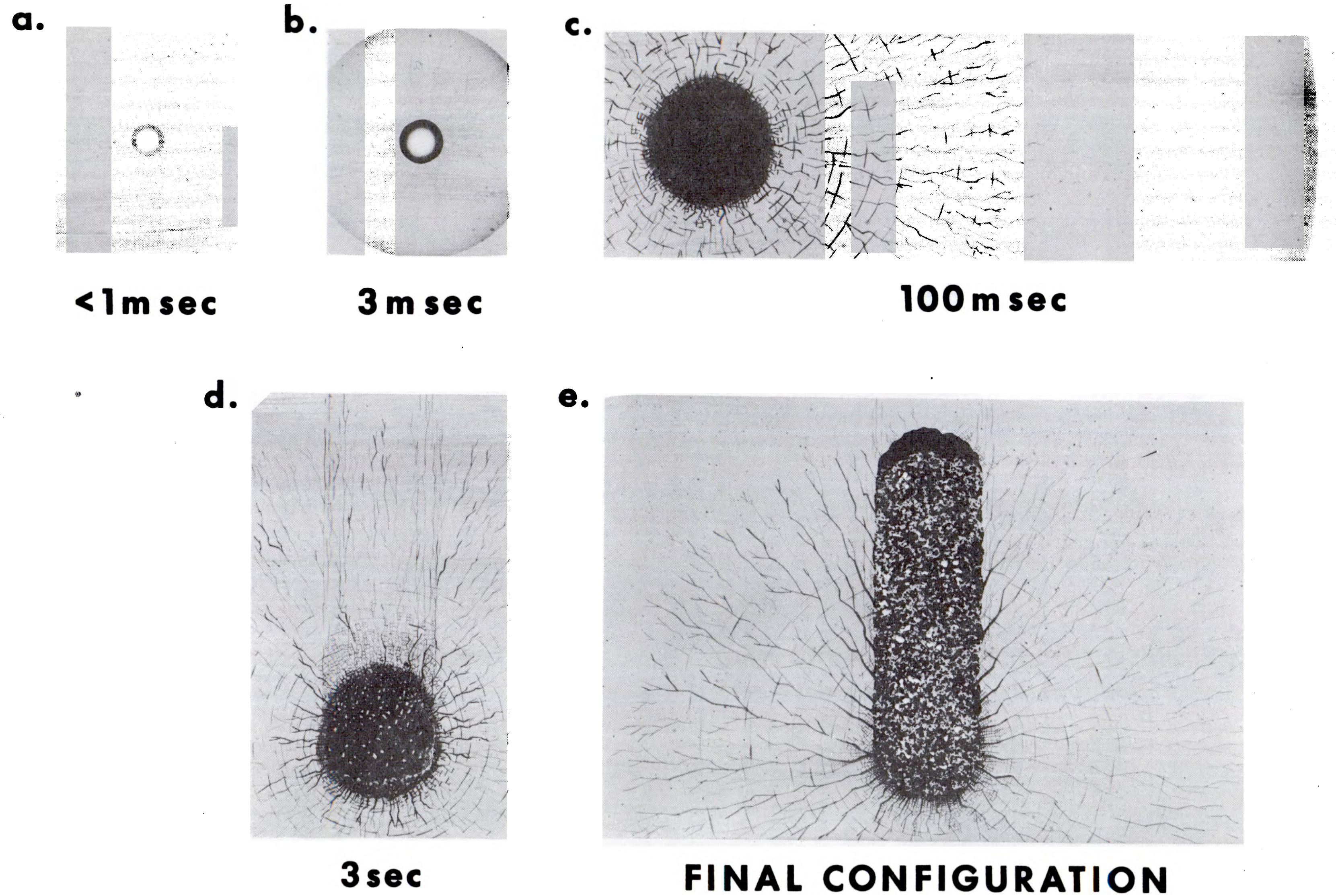

Figure 1

lapse proceeds by the mechanism of successive falling of the roof into the cavity (Figure 1e); if the chimney does not encounter rock strong enough to support a roof span of about one cavity diameter, or, if it does not fill with the more bulky, broken rock, collapse will continue to propagate upward until it reaches the surface and a subsidence crater is formed. The remaining noncondensable cavity gases, now at a pressure of only a few pounds per square inch, are trapped in the rubble and can only reach the surface by diffusion after long times if ever.

Theoretical and experimental knowledge of these long-term phenomena is less well developed than the knowledge of the early phenomena. Cavity pressures have been measured for yields from one to several kilotons. These measurements show that pressure decays with a time constant of a few minutes. A calculational model is under development which will treat in detail the various mechanisms by which energy is transferred from the cavity gas to the surrounding material and will take account of any changes of state which may result from such energy transfer. The model uses calculated cavity conditions at the conclusion of the cavity growth as input for the cavity cooling calculations. It is expected that this model will also include the collapse of the cavity. At collapse time one must consider cooling of the cavity by the introduction of falling rock. One estimates the rate and size of particles which fall into the cavity and, from that, the rate of removal of energy. As this model is further developed, more experimental information concerning cavity conditions will be required. For this purpose further measurements of cavity pressure and perhaps of cavity temperature are planned.

With the collapse of the cavity and the quenching of moisture within the cavity gases, the possibility of any dynamic venting, even through a relatively direct path, is minimized. However, some noncondensable gases remain (predominantly carbon dioxide and hydrogen with some xenon and iodine) at a pressure of only a few pounds per square inch. To reach the surface, the gases must diffuse or migrate through the chimney rubble or through the surrounding material. In effect the process of chimney formation not only reduces the driving pressure within the cavity, but it also creates a filter bed which inhibits the diffusion of these remaining gases toward the surface.

One must then ask whether the chimney constitutes a filter bed of sufficient thickness to prevent these gases from reaching the surface. There is no procedure for calculating the answer to this question, but it can be answered on the basis of experience. On some tests for which there was drillback into the top of the chimney, the position of first contact with radioactive material was noted. This point presumably is the maximum height to which radioactive material has risen in the chimney. In only a few cases has the radioactive material reached the surface or even a level close to the surface.

Of particular importance is the fact that for all shots over 10 kilotons which have been examined in this manner, first contact with radioactivity has been well below the surface. For example, with 100-kiloton shots in which the present burial criteria were followed, radioactivity has never been encountered closer to the surface than about 1,000 feet; for two shots of megaton yield it has not been encountered closer than about 2,500 feet. This experience confirms that the criteria used for the burial of intermediate- and high-yield shots, as intended, are even more conservative than those for the lower-yield tests. Burial criteria are based on the scaled depth of burst (SDOB) which is the depth of burial divided by the cube root of the yield in kilotons. As noted earlier, energy effects are proportional to volume; therefore, the linear distances to which equal effects are noted may be obtained by multiplying the linear distance for a specific effect for a one kiloton yield by the cube root of the yield of interest (in kilotons). Such scaling assumes that energy dissipation is volume dependent. A large amount of experience in the 1-10 KT yield region has empirically established values of SDOB which are safe. Extrapolations to higher yields have kept essentially the same value of the SDOB. Both test experience and calculations indicate that this extrapolation is conservative. A program is in progress to measure stress and material velocity in the neighborhood of high-yield events. As the agreement between calculated predictions and observations has improved, refined methods for computing the optimum safe depth of burial have become available.

In practice even though faults and joints are unlikely paths for venting, it is established practice to avoid emplacing explosives on or immediately adjacent to any known structural discon-

tinuities. The foregoing review of underground phenomenology and geological considerations indicates that with due considerations as to the specific medium and the location of faults, there are no real obstacles to continued effective containment of nuclear explosives fired at sufficient depths underground.

GEOLOGIC CONSIDERATIONS

Underground nuclear detonations are tested in rock formations (including compacted alluvium). Most such formations normally have gross structural discontinuities such as bedding planes, faults and joints. These are fairly accurately studied and mapped by geologists. Such features assume a wide variety of forms, and exactly how they affect containment is hard to determine. Bedding planes will refract and reflect hydrodynamic energy and thereby affect its spatial distribution, but such a redistribution of energy is a second-order effect and causes no concern so long as conservative burial criteria are followed. Of somewhat greater concern are joints and faults. These may range in degree from a single simple undisplaced crack (joint) through a set of parallel cracks to a complex set of cracks along which a significant displacement has occurred (fault).

Joints and faults are of some concern with regard to containment because they are discontinuities, which may be zones of weakness along which material may move with ease. A number of shots have been fired near identified fault systems without adverse effects. On the other hand, there are three examples of relatively shallow buried shots (low-yield) wherein the gaseous effluent escaped along a linear pattern suggestive of a fault. It may or may not be appropriate to infer from this observation that a pre-existing discontinuity controlled the direction of this release. Very close to the detonation where the rock is vaporized, melted, grossly displaced and/or failed, a fault or joint which may have existed will lose its identity as the result of the detonation. As the cavity cools, cracks develop at random sites in the rock radiating from the cavity interface. At the same time, cracks may form as a result of the unloading of the shocked and compressed rock as the cavity pressure drops. This may form cracks which propagate back toward the cavity. As the crack opens from or into the cavity, vapor, liquid, and rock are injected into the crack by the cavity pressure. This phenomenon has been observed in postshot examinations of the area immediately outside the cavity. Cracks into which melt has been injected have been found to extend as far as two cavity radii into the rock. While zones of weakness in more distant regions might appear as a detriment to gaseous containment, there is little hazard to containment in the region closer in because the pre-existing cracks, joints, and faults are filled and sealed with a glass-like coating that forms as the rock vapors condense and harden.

CONTAINMENT OF RADIOACTIVE DEBRIS

Except for excavation events it is current practice to bury nuclear devices sufficiently deep that no radioactive debris is expected to be released to the atmosphere. However, each event is fully assessed prior to being fired so as to minimize the consequences of an inadvertent release. The assessment is made on the basis of a maximum credible upper limit in yield, rather than the most probable yield, and on the unlikely basis that some radioactive release may occur. Even though no release of radioactivity is anticipated, the test is executed only under weather conditions such that a hypothetical release could occur without causing recommended exposure guidelines to be exceeded. At event time, instrumented aircraft are airborne in order to track any release which might occur, so that subsequent action can be based upon actual, not predicted, quantities of radioactivity and cloud trajectories. In addition, every precaution is taken to comply with the limited test ban treaty.

For those cases where an inadvertent release has occurred, the debris can be categorized by the physical phenomenology of the release: that resulting from seepage and that resulting from a "prompt" dynamic release.

While other radionuclides, including tritium, are present in the cavity following nuclear tests fission products have been the predominant radionuclides in inadvertent ventings. These nuclides are mainly categorized as either volatile or refractory. The volatile materials include radioactive noble gases, and the refractory materials include radioactive debris of high vaporization temperature. Material which exists as a radioactive noble gas remains with permanent gases until it decays into a condensable material. Refractory materials condense rapidly as the cavity cools.

In underground tests the puddle formed soon after the explosion from the condensed and resolidifying material is enriched in refractory fission products (or depleted in volatiles), and the chimney is enriched in relatively volatile materials which diffuse with cavity gases into the void spaces formed from collapse. The chimney material acts as a filter so that the only radioactive material which could seep to the surface to reach the atmosphere consists of noble gases and a relatively small amount of iodine. Consequently, the ratio of volatile to nonvolatile material in the released debris distinguishes seepage from prompt venting. A distinction can be made between the two types of venting on this basis.

When the gaseous radioactivity trapped underground following a test can find a path through the chimney rubble it may seep to the surface. Seepage, when it occurs, commences from as early as a few minutes to as late as many hours after the detonation and has continued, in some unusual instances, for a few days. The amount of radioactivity released by seepage has never been observed to be greater than a very small fraction of that formed.

The second category of venting, one that has occurred less often than seepage, is the "prompt," dynamic release, in which material is released with considerable kinetic and thermal energy. This type of venting, if it is going to happen, will probably occur before cavity collapse either through ground fissures or because of a stemming failure. In those cases (a few low-yield events) when dynamic venting has occurred, the radioactivity released was at most a few percent of that formed underground.

The real measure of success in the containment of underground nuclear explosions is revealed in the record. To give a representative picture of containment results 171 tests performed from August 5, 1963, through March 1, 1969, were examined. This number includes all announced nuclear tests except those which were fired for cratering purposes. The tests included some fired in vertical drilled holes and some in horizontal tunnels. Some of the holes and tunnels were unusual in that there were pipes leading away from the emplacement location equipped with mechanical closure devices and valves. Of that total number of tests, 14 released sufficient radioactive debris to be detectable outside the

controlled area of the test site. Of these 14, most occurred because of failures in the stemming or in mechanical closure devices on the pipes and tunnels. With these ventings, radiation levels and doses at populated offsite areas were in all cases less than those recommended as limits by the Federal Radiation Council as radiation protection guidance. Other tests showed some radioactivity as measured on detection instruments on the test site, but these did not cause radiation levels that could be detected outside the controlled area of the test site.

By far the greatest number of tests have been fired in vertical holes, without pipes or other direct communication with the surface, and stemmed with sand, gravel and cement from just above the test device to the ground surface. It may be helpful to examine the record for containment of tests fired under these somewhat standardized conditions. Considering all tests in this general category (totaling about 200) fired since the resumption of nuclear testing in 1961, only 10 released radioactivity of any consequence, and of these, only 3 released radioactivity that could be detected outside the controlled area of the test site. Of these 10, 3 vented through ground fissures commencing within the first minute after the explosion, and the other 7 seeped radioactivity after cavity collapse. Of the 10, 7 were tests of devices with yields less than 5 kilotons, 2 had yields between 5 and 20 kilotons, and 1 had a yield between 20 and 200 kilotons. One of the 10 leakages occurred with a device that was fired in carbonate rock. Carbon dioxide produced from the carbonate rock by the detonation remained as a cavity gas so that the noncondensable gases containing radioactive xenon percolated upward through the chimney under unusually high pressure and reached the surface after about 12 hours.

In summary, when radioactive effluent has been observed following some shots, it has represented only a small fraction of the total radioactivity produced in the shot. It has been most frequently observed in connection with low-yield shots at late times; that is, after the collapse of the cavity. Each of the various cases of radioactive leakage was carefully investigated in order to determine the cause and to profit from the experience. Because of these leakage experiences, standards for containment have been adjusted and stemming techniques have been improved continuously so as to correct deficiencies. The results in containing high-yield events and intermediate-yield events have been entirely satisfactory; none of the test events in these yield categories has produced radioactive leakage.

GROUNDWATER CONTAMINATION AND MOVEMENT

Underground nuclear explosions produce radioactive debris. Hence, it becomes of importance to make sure that these radioactive contaminants, having been placed in the underground environment, do not become a problem.

As discussed in preceding sections of this report, most of the radioactive material is retained within the explosion cavity following underground nuclear tests. Some part of this radioactivity is added to underground water either directly, when the explosion is below the water table, or indirectly by water percolating downward to the water table. In either case groundwater is the transport vehicle in movement of radionuclides underground. Since tritium, a radioactive form of hydrogen, associates itself with oxygen to form radioactive, tritiated water which behaves as the normal water and, therefore, moves as a part of the groundwater, that radionuclide is important in the groundwater problem.

Since both the cavity volume and the tritium amount are roughly yield dependent, the cavity water will probably have a tritium concentration that is roughly uniform for all cavities of the same age; hence the tritium concentration in the cavity water is almost independent of yield. In the low permeability media at test sites the rate of groundwater movement is slow. The tritium problem becomes alleviated because tritium decays during its lengthy travel underground.

Of the other radioactive debris following an underground nuclear test, the refractory radionuclides remain within the explosive cavity while most of the volatile radionuclides remain in the chimney. Much of the refractory debris is permanently contained within the glass-like material that lines the cavity walls and solidifies on the floor as the cavity cools. There it remains to decay, relatively inaccessible to groundwater.

It must be assumed that the remaining radionuclides gradually dissolve in groundwater that will slowly seep into the surrounding rock. However, most of these dissolved materials tend to be adsorbed or attached, at least temporarily, to the rock through which the migrating water travels so that effectively these radionuclides move even more slowly than the groundwater. Calculated estimates based on water movement, radionuclide adsorption characteristics, and radioactive decay rates lead to the conclusion that water supplies even a few miles from test locations are not in danger of being contaminated.

In order to arrive at this conclusion, groundwater is studied in several ways so as to gather adequate information about subsurface conditions. In addition to regional studies which evaluate the broad framework of the hydrologic environment, there are investigations to evaluate local conditions at proposed nuclear event sites. At and near the NTS the U.S. Geological Survey has compiled water-level and water-flow records on over 100 wells, test holes, and emplacement holes, as well as at numerous springs, for use in defining areas of groundwater recharge, water loss by evaporation, flow paths underground, and discharge points. This information is augmented by chemical and radiochemical analysis of water, including age-dating of underground water by radionuclide analysis techniques. On the basis of the composite results of these various studies, underground water travel has been found to be so slow (0.02 to 2.0 feet per day) that contaminated water would take an extremely long time to leave the NTS. Taking Yucca Flat as an example, the groundwaters have been underground several thousands of years and their average rates of movement are believed to be significantly less than one hundred feet per year.

Underground explosions evidently have little effect upon the underground water transport. In measurements in nearest wells at 60 to 70 kilometers from the sites of large nuclear explosions, water levels have never fluctuated more than a few centimeters at the times of tests. At one location at NTS a well that was drilled in the rubble chimney for diagnostic sampling was retained and has been used for radiochemical sampling of water in the rubble chimney and for monitoring the rate of chimney filling. It did not fill to the preshot water level until more than

three years after the shot. Several months after the shot a well was drilled just outside and in the direction of deepening water tables (i.e., down-gradient) from the rubble chimney, terminating in a permeable aquifer which lies a few hundred feet below the explosion point. This well has been pumped and sampled. Five years after the detonation, contaminants have not been detected in the water, even though water in the rubble chimney contained radioactivity. Periodic sampling of this hole is continuing.

While this specific experiment is not repeated for each test, exploratory holes are drilled extensively at the test sites. For example, there is at least one geological and hydrological exploratory hole drilled at the prospective site for each test on Pahute Mesa on the NTS. This is done to test for the chemical properties and permeability of the rock, to determine the groundwater table, to verify that there are no discontinuities such as faults, to verify that there is no passage through which underground water may travel (aquifers) and to make sure that the level of relatively permeable carbonate rock is at least several hundred feet below the intended test explosion depth.

From experimental studies such as these it becomes increasingly evident that the underground radionuclides will not reach discharge areas outside the NTS at levels higher than are recommended as permissible concentrations by the guides of the Federal Radiation Council.[1] This is verified through periodic checks for radioactivity in test holes and wells at and around the test site.

The same general procedures of geologic and hydrologic analysis of proposed emplacement sites described above are used at test locations other than NTS. In Central Nevada, hydrological studies disclose that groundwater occurs in valley fill, volcanic rocks, and carbonate rocks. Again, the highly permeable carbonate rocks underlie the area at depths generally greater than 7,000 feet. Depths to water are shallower at Central Nevada than at NTS because precipitation and recharge rates are greater at Central Nevada. The depth to water is generally less than 600 feet below land surface. Most of these valleys are filled to the point of permitting direct evaporation or spring discharge in the lowest places where the land surface intersects the water table. For Hot Creek Valley, site of present test activity in Central Nevada, some of the groundwater eventually reaches discharge areas in Railroad Valley. Groundwater velocities computed from hydraulic tests of exploratory holes in valley fill and volcanic rocks are less than 200 feet per year. While Central Nevada differs from the NTS in that there is no large exclusion area surrounding the test location, radionuclide contamination should not be a problem. This situation will, of course, be closely monitored.

Although the water tables at Amchitka Island are shallow and there is sufficient precipitation to maintain numerous lakes and small streams at the island's surface, the rock deep underground in the test locations has such a low permeability that transport rates for radionuclides are expected to be extremely slow. Several faults are known to exist at Amchitka, but the planned test holes have been drilled so as to avoid these discontinuities. On the basis of information collected to this date, radioactivity transport by groundwater will be extremely slow. If, however, some radioactivity should be transported by groundwater to faults, it is conceivable that minute contamination might gradually reach the sea in undetectable concentrations.

In summary, groundwater problems are avoided in underground testing by using rock that is relatively impermeable to water and devoid of faults and discontinuities. There is extensive testing of underground conditions to verify that the required conditions do exist. Drinking water for the NTS is drawn from wells at Yucca and Frenchman Flats. Our monitoring of this water to assure its safety has borne out the Commission's confidence that no water supplies, either on or offsite, will become contaminated through underground nuclear testing.

[1] Federal Radiation Council Report No. 1, May 13, 1960; Background Material for Development of Radiation Protection Standards.

GROUND MOTION INDUCED BY NUCLEAR DETONATIONS

PREDICTION OF GROUND MOTION

Ground motions generated by underground nuclear detonations have been studied since 1957, with extensive study since 1964. The results of these studies, together with the understanding of seismic phenomena that has been gained through long experience with the effects of earthquakes and high-explosive detonations, have enabled us to develop techniques for predicting the ground motions caused by underground nuclear explosions.

At a particular location, the ground motion resulting from an explosion depends not only on the yield and the distance of the location from the site of the explosion, but also on the nature of the medium in the vicinity of the explosion, the structure of the earth's crust between the explosion site and the location in question, and the surface material at the locality. It has been found that for shots under the water table (which include all the high-yield events at Pahute Mesa, Central Nevada, and Amchitka), source media behave quite similarly. When the dimension of the test area (such as Pahute Mesa) is small compared with the distance to the location of concern (such as Las Vegas), differences in propagation paths are minor. Other factors being equal, the ground motion as measured on alluvium is two or more times that on hard rock. Rarely does a combination of propagation path and local response result in motions at a given location considerably higher than would be expected for its distance from the shot. Of over 100 locations instrumented, only two anomalous locations have been found. To ascertain the existence of any such locations, lower-yield devices are detonated first in new test areas to determine whether or not abnormally high ground motions might occur in the vicinity and to otherwise prove the new location as being suitable for larger yields.

Earth motions have been measured on over 250 nuclear events at NTS at distances ranging from a few miles to over 300 miles for the larger events. The results have been consolidated into empirical scaling relations for maximum velocity, acceleration, and displacement as a function of distance. In general, data from the FAULTLESS event in Central Nevada and the GASBUGGY event in New Mexico follow these relations and give confidence that NTS experience can satisfactorily be applied at the supplemental test areas, provided there is proper consideration of anomalous locations that may exist near those areas. In addition to establishing relations for peak values, the seismograms recorded at many population centers in Nevada have been analyzed to identify fundamental ground motion frequencies, and the capability to predict ground motion amplitudes in various frequency intervals has been constantly improved. This is particularly important for predicting response of structures.

Present capability for predicting ground motion is substantiated by statistical analyses of existing data. The accuracy of the predictive techniques is illustrated by the following comparison of measured and predicted ground motion in Las Vegas for the recent BENHAM event of about one megaton yield:

	Acceleration	Velocity	Displacement
Predicted	0.008 g	1.3 cm/sec	0.39 cm
Measured	0.006 g	1.14 cm/sec	0.43 cm

These data also illustrate why events of about one megaton are perceptible in Las Vegas. Very perceptive people will notice ground acceleration greater than about 0.001 g, and most individuals will sense accelerations of 0.005 g and above. These accelerations, however, are well below those at which structural damage occurs.

DAMAGE TO STRUCTURES

One method of prediction of potential damage to buildings and other structures uses an engineering parameter called the elastic response spectrum of the structure. The response spectrum is calculated from the peak responses of a series of damped oscillators of different fundamental frequencies that have been subjected to a displacement history analogous to the ground

motion induced by an earthquake or underground nuclear detonation.

A technique has been developed for predicting building response by statistically analyzing a series of spectra obtained over a range of yields and distances from the explosion. The response prediction is applied using analytical engineering techniques to estimate the probability of damage to structures.

From the standpoint of structural dynamics, damage to one- and two-story structures can be correlated with the acceleration calculated by the response-spectrum procedure. Of course, since buildings differ in construction, age, and state of repair, all are not equally sound. Therefore, the likelihood that given accelerations will cause non-structural damage, e.g., cracked plaster, can be stated only in terms of probabilities. Probabilities, even for the towns closest to the test site, are low. For tests prior to BENHAM no claims of damage to any inhabited structure in Nevada have been found valid. A few claims of non-structural damage (i.e., damage which does not cause structural weakening—such as surface plaster cracks) after BENHAM have been found valid and have been settled.

High-rise buildings in Las Vegas are analyzed individually, and their calculated capacities to withstand damage are compared to the demands imposed upon them by ground motions. These analyses indicate that maximum ground motions in Las Vegas due to events in Nevada may be approaching amplitudes which could produce superficial damage (non-structural damage) in one or two of the high-rise buildings. Estimates of the probability of such damage are difficult to derive. Earthquake data are extremely sparse and therefore of limited utility. To date, no claims of damage to high-rise buildings in Las Vegas have been made.

In addition to the response of buildings, the response of dams and mines to the ground motion from Nevada detonations has been evaluated. Since subsurface motions are considerably less than surface motions at a given distance from the detonation, no damage to mine workings off the test site is expected, nor has any been found; in fact, no damage due to high-yield tests has been found in tunnels on the test site. This finding also applies to water wells which have been subjected to earth motion generated by high-yield nuclear detonations.

As for major dams, which are massive and well-engineered structures, analysis indicates that no damage is expected. In the case of Hoover Dam, motions induced by natural earthquakes in the vicinity of the dam have been about a hundred times greater than the motions recorded from nuclear detonations. Of the many earthquakes which have occurred around and under Lake Mead, none has caused known damaging seiches (long-period oscillations of a lake or landlocked body of water) or slides, or other failures of the reservoir. On the basis of observations and calculations, the possibility that nuclear tests might induce slides or seiches in the Lake Mead area is considered negligible.

EARTHQUAKES AND AFTERSHOCKS

It has long been recognized that seismic tremors follow underground nuclear detonations. For low-yield events, most of the seismic tremors are associated with the processes of cavity collapse and chimney growth. With the higher-yield explosions in the past two years, however, related seismic activity has been observed which originates outside the environment of the cavity and chimney. Such phenomena were more pronounced after the FAULTLESS event (January 19, 1968) in Central Nevada and the BOXCAR event (April 26, 1968) on Pahute Mesa than after previous events. In response to these observations, the AEC sponsored a large-scale effort by several agencies, including seismological observatories, to make a detailed study of the aftershocks from the recent BENHAM event (December 19, 1968) at the Nevada Test Site. An ad hoc committee of geophysicists provided advice and guidance in this effort. Participating in the acquisition and analysis of the data were the U.S. Coast and Geodetic Survey, the U.S. Geological Survey, the University of Nevada, the California Institute of Technology, the Lamont Geological Observatory, the Colorado School of Mines, the Massachusetts Institute of Technology, the Earthquake Mechanism Laboratory of the Environmental Science Services Administration, Environmental Research Corporation, the Lawrence Radiation Laboratory, and the Sandia Laboratories.

Preliminary results from BENHAM were summarized at a recent meeting of these investigators. The BENHAM detonation resulted in an-

ticipated transient strains and compression of the earth. Long-period compressions observed at 30 and 71 kilometers decayed within an hour to preshot conditions and thus resulted in no permanent strain buildup. On the other hand permanent strains of greater than one centimeter in 10,000 meters were measured within 18 kilometers of ground zero. Only short-time transients were observed at a strain measuring installation 240 kilometers from NTS. Formation pressures and water levels measured in wells sometimes show substantial transient fluctuations but no permanent changes have been produced outside the immediate vicinity of the shot point. Examination of several faults beyond 10 kilometers from the detonation has not detected any slippage caused by nuclear events. Included were such faults as the Death Valley and Owens Valley faults, the San Andreas fault system in California, and the Fairview Peak—Dixie Valley faults in northern Nevada.

Microearthquake observations taken before and after the shot at eleven offsite locations reveal no fluctuations in the level of the local seismicity which can be related to BENHAM.

The present status of understanding of the earthquake and aftershock effects of underground nuclear detonations may be summarized as follows: A high-yield nuclear detonation is accompanied by fault displacements similar to those observed for some earthquakes. The faults undergo all or most of their event-related displacements soon after the shock wave has passed. The displacements occur along preexisting faults, with relative motions apparently consistent with those having occurred in the geologic past. Current data indicate that the distance along a single fault to which fault motion extends depends linearly on yield. The maximum distance at which fault displacement, caused by nuclear explosions, has been observed to date is less than 10 kilometers. Seismic energy radiated by faulting has been observed to be less than the seismic energy radiated by the nuclear event, as ascertained by investigations of teleseismic surface waves.

Aftershocks occurring after high-yield tests are limited in both extent and size. For all events to date, including the BENHAM event, the amplitude of the seismic waves from the largest aftershock observed is a very small fraction of that from the nuclear event. Nearly all the aftershock sources lie within 12 kilometers of the nuclear detonation. Many of the shocks appeared to have occurred at locations which lie along lines that can be related to mapped faults. Those few seismic events located as far as 20 to 40 kilometers from the site of the detonation may be a part of the existing microearthquake pattern and cannot at this time be conclusively related to the preceding nuclear event.

The evidence now at hand indicates that the yields anticipated at the NTS will not result in damaging earthquakes or aftershocks. However, there is concern on the part of some earthquake experts that there is no basis for eliminating the possibility that serious earthquakes might be induced by larger-yield nuclear tests. These questions are being given additional study, and all appropriate underground tests are being instrumented for this purpose.

The Amchitka test area merits special mention because it is located near one of the earth's most seismically active regions. Inasmuch as earthquake mechanisms are not completely understood, no absolute statements can be made about the possibility of triggering an earthquake of large magnitude in this area. Should an earthquake occur during the testing program, its significance with respect to the question of test safety may be judged by considering the effects of the extremely large (estimated body wave magnitude between 7.5 and 8) Rat Island earthquake (February 4, 1965) which originated about 20 miles south of Amchitka. By way of comparison the largest underground nuclear explosion that had been fired by February 1969 had an equivalent body wave magnitude of about 6.3. As was demonstrated in the Rat Island earthquake, there is no direct seismic hazard, since the source is so remote from centers of population. The remaining question of tsunami generation is covered elsewhere in this report. Here it is sufficient to say that the Rat Island earthquake did not result in damaging water waves beyond the nearby uninhabited islands.

TSUNAMIS AND OTHER WATER-WAVE EFFECTS

A tsunami is a train of travelling, long period, gravity waves generated in the ocean by a large scale impulsive disturbance.

In the open ocean, tsunami waves are of low height (about one foot or less), long period (in excess of four or five minutes), and very long wave length (100 miles and more), and they travel with speeds sometimes exceeding 500 miles per hour depending on the ocean depths. The waves are destructive only when they approach a shoreline where refraction, shoaling, and resonance effects combine in a very complex manner to increase both the horizontal current speed and the height of the waves, thus sending them onto the land, far above the normal tidal water levels. Research has shown that the magnitude of coastal enhancement depends strongly on local submarine topography and direction of wave approach, and weakly on the details of the open water disturbance. Thus, some particular coastal regions have been found to be much more susceptible to tsunami inundation over the years than are others. Furthermore, this susceptibility is independent of the distance from the source.

Nearly all naturally occurring tsunamis are closely associated with large submarine earthquakes of Richter magnitude greater than about 6.5 and with focal depths less than 30 miles. The principal mechanism of generation is ascribed to vertical dislocations of the sea floor. Since the tsunami source is at great depths in the ocean, the exact details of the mechanism are extremely difficult to ascertain. Other phenomena that have been considered as possible causes of tsunamis include: volcanic explosions and caldera collapses, landslides, both submarine and subaerial, the interaction of the water with very long-period seismic surface waves, and, the more recently suggested possibility, large nuclear explosions.

There is little direct evidence that energy in long-period seismic surface waves or submarine slides could be coupled to sea waves so as to cause major, destructive, ocean-wide tsunamis. Those tsunamis caused by volcanic explosions have been observed to be comparatively rare and of importance only over a limited area. Waves generated by landslide debris falling into the water in fjords and along coastlines are a common accompaniment of large natural earthquakes, but the major effects, although sometimes locally intense, are limited to a few tens of miles at most from the slide areas. In an uninhabited test site in the Aleutians, a few such slides can be expected but these do not constitute any offsite public safety problem.

The characteristics of the mutually connected submarine earthquakes and tsunamis which account for the great bulk of cases in nature provide a basis for evaluating any potentially hazardous effects of large underground nuclear explosions located near a shoreline:

1. There is a general statistical correlation between the Richter magnitude of the earthquake and the "magnitude" of destructive potential of the associated tsunami. The historical data show that measurable tsunamis are unlikely to result from earthquakes smaller than magnitude 6.5 but that potentially dangerous ocean wide tsunamis may be expected when the magnitude exceeds about 7.5. For an earthquake which results in a major tsunami, the energy in water waves is approximately one-tenth that radiated as seismic waves.

2. There is a correlation between earthquake focal depth and tsunami magnitude in the sense that for a given earthquake energy, shallower earthquakes tend to produce larger tsunamis. Tsunamigenic earthquakes are limited to focal depths of 30 miles and less.

3. The extent of the area of tsunami generation coincides with the region of seismic activity including the aftershock area as well as the epicentral region. (This is well illustrated by the great 1964 Alaska earthquake where the initial high magnitude epicenter was actually under land just north of Prince William Sound, whereas the main tsunami generation area was in the Gulf of Alaska in an area which subsequently proved to be closely coincident with the after-

shock area.) Furthermore, the dimensions of the aftershock area are directly related to the length of fault over which motion occurs and hence to the earthquake energy. Since the aftershock areas are often elongated and especially so for the largest earthquakes, the large tsunamis often possess highly directional properties as well. In the case of major earthquakes, the fault lengths are very large—about 800 miles for the 1964 Alaska earthquake (magnitude 8.4) and about 70 miles for an earthquake at the "dangerous tsunami" threshold (magnitude of about 7.5).

The submarine slide hypothesis was originally proposed to account for those puzzling cases in which tsunamis were observed although the epicenters of the time-associated earthquakes were located on land. (More recently detailed study of earthquakes has shown that the initial epicenter is usually near one end of the active fault zone, which would better explain such tsunamis since the area of faulting could easily extend under the sea.)

In 1929 the plausibility of the seaslide mechanism was apparently strengthened by the discovery of large turbidity currents probably associated with extensive landsliding after the Grand Banks submarine earthquake of that year. However, subsequent calculations and laboratory experiments indicated that freely propagating water waves are not created by the relatively slow (i.e., 15 to 60 knots), dilute turbidity current itself. Rather, it appears that both the waves and the turbidity currents are caused by an initial, smaller slump. The area over which turbidity currents were observed in 1929 was indeed vast, but the area of original slumping is considerably smaller and can likely be restricted to the aftershock area of this earthquake. The 1929 Grand Banks earthquake was large enough (magnitude 7.2) that the localized tsunami damage in Newfoundland 250 miles away can be explained by analogy with Japanese experience in terms of faulting alone without invoking an *ad hoc* slide-wave coupling mechanism. Even if slumping displacements in the fault area may have played an important part in the generation of the Grand Banks tsunami, that earthquake took place in an area of high sedimentation rate and infrequent seismic activity where sediments could be expected to be unstable. In contrast, the western Aleutians is an area of very low sedimentation rate and frequent, large earthquakes.

Additional evidence against the seaslide hypothesis is that major tsunamis are *always* associated with earthquakes. Many undersea slumps and turbidity currents are known that were not triggered by any recorded earthquake and for which little or no water-wave activity could be observed. In summary, although submarine landsliding may be responsible for some small local tsunamis, it is extremely difficult to find evidence of landslides of adequate volume, area and coherence to account for the major ocean-wide events.

The possible coupling mechanisms to be considered for a near shore underground nuclear explosion at Amchitka can be listed as follows:

1. *Permanent vertical ground displacements* (including surface faults) *set up by the explosion.* A doming of the surface in the immediate vicinity of ground zero and associated vertical displacement along pre-existing fault planes passing near the shot point are expected on the basis of explosions of comparable size at the NTS. Only those parts of the displacements lying under the ocean adjacent to the island will be effective in wave generation. From NTS experience, it appears to qualified geologists that the underwater portion of fault displacement to be expected at Amchitka is less than that which would be expected from a magnitude 6.0 earthquake. Natural Aleutian earthquakes of similar size have been observed to give rise to only minor (though instrumentally measurable) tsunamis. This generation mode is expected to be the only important one of those listed here.

2. *Submarine landsliding.* Since Amchitka lies in the western Aleutians, cut off from any major sediment source and in a very seismically active area, the possibility of triggering any major submarine slump is believed to be remote, as discussed above. Only minor, very localized wave effects are to be expected from this source.

3. *Triggering of a major submarine earthquake.* The probability that a large underground nuclear explosion will trigger a larger earthquake (in terms of magnitude) is discussed elsewhere in this report. *If* such a submarine earthquake were to be triggered, any magnitude greater than 7.0 would likely give rise to a perceptible wave. A long-range tsunami of potentially destructive proportions is almost a certainty from a submarine earthquake of magnitude greater than 7.5. That such a wave is not necessarily destruc-

tive is demonstrated by the Rat Island earthquake, which was the largest earthquake in the world during 1965. The epicentral location of this quake was within 20 miles of Amchitka, and its magnitude was about 7.5 to 8. The tsunami from this earthquake registered on tide gauges throughout the Pacific, but caused no damage anywhere except for some minor flooding at an uninhabited island within 50 miles of the generation area.

4. *Cavity and crater collapse.* For contemplated tests, the size of the collapse feature is too small and located too far away from the shoreline to be able to intersect the ocean.

5. *Coupling from long-range seismic surface-wave modes.* As mentioned above, this is an unlikely coupling mechanism because the seismic wave velocity is so much greater than the water-wave velocity that the coupling efficiency is very small. In the case of an underground nuclear explosion as contrasted to a major earthquake, coupling is even less efficient because explosions are known to radiate far less energy in seismic surface waves than do earthquakes having the same body wave magnitudes.

There is no reason to expect that there will be tsunami-like wave effects of other than minor proportions localized near the test area. The best evidence for this is the vast source area and energy associated with a major natural tsunami as compared with the small source area and energy associated with nuclear tests.

However, a program of theoretical and experimental research, together with appropriate supporting field measurements at NTS and Amchitka, has been underway for several years and is expected to continue as long as contemplated test programs require consideration of tsunami effects.

MANAGEMENT CONTROL FOR SAFETY IN NUCLEAR TESTING

No nuclear test is conducted unless the Atomic Energy Commission is convinced that the test can be conducted safely. Each test is an experiment designed to yield specific information, but regardless of the importance of this information, safety is the overriding consideration in the final decision to conduct a given test and in the direction of the test program as a whole. In the foregoing sections of this report the effects of underground nuclear explosions have been discussed. This section addresses the question of how this knowledge is systematically applied to ensure safety in the underground nuclear test program.

Within the AEC, the Commission exercises final authority with respect to providing reasonable assurance of public health and safety. In these matters the Manager of the Nevada Operations Office (NV) is responsible to the General Manager of the Atomic Energy Commission to coordinate the planning and execution of nuclear weapons tests and other nuclear explosion tests, to develop equipment and processes to assure safe and effective operations, and to assure that appropriate consideration is given to protection of health and safety from hazards associated with these test functions.

The Commission's program for underground nuclear test safety can be regarded in two general aspects that are carried out concurrently and on a continuing basis: one, the evaluation and control of effects associated with each test shot so as to avoid creating hazards; and two, the continuous observation and research that provide the data on which those evaluations are based.

The planning for a nuclear-explosive experiment begins well in advance of the ultimate detonation date. It originates when a need is recognized for information that can be obtained only by detonating a nuclear device. Most nuclear experiments are designed by the Los Alamos Scientific Laboratory and the Lawrence Radiation Laboratory, both operated for the Atomic Energy Commission by the University of California. These two laboratories, plus the Sandia Laboratories and the Defense Atomic Support Agency within the Department of Defense, are also involved individually in fielding and executing specific nuclear tests. From the beginning, the experimental firings are designed with two objectives in mind: to do the experiment safely and to obtain the required information. In designing a test, the laboratory that designs the experiment determines how deeply the explosive must be buried, how the emplacement hole must be stemmed, and how the explosion will affect the medium surrounding it. These and other considerations involving safety are thus an integral part of the plans for each test.

On the basis of design information from the cognizant laboratory plus other pertinent information about the proposed test, NV exhaustively evaluates the effects of the proposed test. Depending on the complexity of the test, many different groups may take part. The guiding principle behind this evaluation is that of checks and balances and redundancy—details of the plan will be scrutinized many times by many people from many points of view.

Every test, large or small, simple or complex, is critically examined by the Nevada Operations Office of the Atomic Energy Commission. Every aspect of the test is analyzed for potential risk. When problems are spotted, they are referred to consultants from universities and private industry, private contractors, and to appropriate government agencies.[2] If it is determined that the

[2] The following is a list of the principal sources of information used by the Nevada Operations Office:
- Panel of Safety Consultants—seismology, soil mechanics, rock mechanics, structural response, construction engineering, hydrology, geology;
- Nevada Southern University (Southwestern Radiological Health Laboratory, Public Health Service)—offsite radiological safety;
- Reynolds Electrical and Engineering Company—NTS onsite radiological safety;
- Eberline Instrument Company—radiological safety at supplemental test sites;
- ESSA-Weather Bureau—weather prediction;
- ESSA, U. S. Coast and Geodetic Survey—seismology;
- U. S. Geological Survey—geology and hydrology measurements;
- Isotopes Incorporated—groundwater contamination predictions;
- Environmental Research Corporation—ground motion predictions;
- John A. Blume Associates—structural damage predictions;
- Bureau of Mines—mine and well inspection; and
- Fenix and Scisson—drilling and mining consultant.

test as designed poses any potential hazard to the public, the test plans are revised to eliminate the potential hazard and are then reevaluated.

The Test Evaluation Panel, which deals specifically with containment, is intimately involved in every test. Its primary responsibility is to ensure that every feasible measure is taken to prevent inadvertent release of radioactivity. It reviews every factor involved in the possibility of radioactive release—the chronology of events relating to construction of the emplacement hole (often reveals important information about underground geology and hydrology), its location relative to satellite holes, instrument holes, and other emplacement holes in the vicinity, and details of the geology of the emplacement medium. Of major concern is the stemming by which the constructed openings in the rock will be sealed before the detonation. The Test Evaluation Panel periodically reviews the progress on each emplacement site until preparations for the test are completed, and its findings are reviewed by Atomic Energy Commission Headquarters in Washington. Unless the Panel is satisfied that all reasonable measures have been taken to effect containment, the test will not be carried out.

When all parties at NV are assured that the test can be conducted safely—that it will cause no excessive ground motion, that it will cause no injury to people on or off the test site and that no other problems are identified—the Manager of NV requests execution authority from the Commission. On a quarterly basis the Atomic Energy Commission requests general approval from the President for tests being planned for the three month period to follow. Having obtained this broad authorization, final specific approval for every U.S. nuclear test must come from the Commission itself; in addition, the President has occasionally reserved final approval authority for certain tests.

Once a test has been approved at the highest levels, the decision is conveyed to the Manager, NV, who delegates certain operational and executive authority to the NV Test Manager.

During the final weeks and days preceding a test, the NV Test Manager and his Advisory Panel pay particularly close attention to test preparations, becoming completely familiar with all details relating to that impending test. Finally, when all is in technical readiness, the NV Test Manager is authorized to conduct the test. Commencing the day before the test, the Test Manager and his advisors double check that all of the necessary preparations have been completed and necessary precautions have been taken.

Three hours before shot time, the members of the Advisory Panel meet again and repeat their deliberations, paying specific attention to the current weather situation. They remain on the scene with the Test Manager until the shot has been fired and it has been verified that no venting or other serious accident has occurred. At any time during the countdown, up to the final second, the Test Manager can stop the test if any condition arises that might jeopardize safety. At the scheduled time if all firing conditions are met the event is fired.

Precautionary arrangements will have been made to evacuate any people who might be exposed to radioactive effluent in case the shot vents. Off the test site, the Public Health Service posts mobile teams who are equipped for two-way radio communications and prepared to move on immediate notice. If there were any possibility that people would be exposed to dosages of radioactivity approaching the accepted FRC exposure guidelines, they would be temporarily evacuated from the area to minimize the radiation dose they would receive.

In the case of high-yield shots, the populace in areas that may receive perceptible ground motion is notified well in advance of the test. This notification is more than a mere courtesy; those who may be in a hazardous position, such as miners and steeplejacks, can take care that they are out of danger when the ground motion occurs.

The above discussion gives an indication of the degree of management control that is exercised to ensure safety in individual test shots. In support of the test program, the Commission administers a broad program of research and development, much of which applies directly to safety in testing. Two activities in this category, study of the release of radioactive effluent and the effects of groundshock, are guided by the recommendation of two subcommittees of the NTS Planning Board, an advisory group to Manager, NV. The Radioactive Effluent Subcommittee reviews the data that are accumulated by monitoring stations located at various distances from the test site, aids in coordinating the data-gathering

apparatus, and advises NV management as to our long-term success in controlling the release of radioactivity. Similarly, the Groundshock Subcommittee reviews the accumulated data on predicted and observed ground and structural motions caused by underground nuclear explosions and advises NV management in cases where experience shows that groundshock is liable to cause problems in conducting a test.

The Atomic Energy Commission retains a Panel of Safety Consultants, which is composed of recognized authorities, several of whom were recommended by the National Academy of Sciences, in such subjects as hydrology, geology, structural engineering, geophysics, and soil and rock mechanics. These scientists review the safety programs associated with nuclear testing. They provide valuable advice as to what subjects need to be explored further and what directions new research should take. They are also concerned with the long-range effects of testing, such as the distribution and accumulation of radionuclides in the environment and the structural damage effects of high-yield explosions.

From time to time *ad hoc* panels of experts from outside the Atomic Energy Commission are convened to study new or unusually difficult problems. Like the Panel of Safety Consultants, these *ad hoc* panels provide advice on the Commission's safety programs, which is always a valuable service.

To promote awareness among the public of the safety programs and to disseminate to the scientific community the new knowledge derived from the associated studies, the Atomic Energy Commission encourages the NV safety contractors to publish their findings. More than 50 papers, covering the entire range of subjects involved in the safety of underground nuclear testing, are in preparation to be published in professional journals and/or delivered at symposia during 1969.

Several Atomic Energy Commission laboratories and contractors are conducting research programs in biology, medicine, and radioecology —in particular, on the effects of radionuclides in man's food chain. Native plants and animals living near detonation sites at the NTS are under continuous surveillance to determine the biological effects of the radioactivity in their environment.

Thus, through comprehensive control of testing procedures, through a redundant system of independent checks and balances, and through a broad program of evaluation, criticism, and research, the Commission does everything necessary to ensure that the nuclear testing program causes no hazard, either immediate or future, to the public.

SELECTED SUPPLEMENTAL READING LIST

GENERAL

USAEC, Safety Involving Detonation of Nuclear Devices, NVO–28 (Revision)

USAEC, Technical Discussions of Offsite Safety Programs for Underground Nuclear Detonations, NVO–40 (Revision)

UNDERGROUND PHENOMENOLOGY

NVO–40 (Revision)

Germain, Lawrence S. and Kahn, J. S., Phenomenology and Containment of Underground Nuclear Explosions (UCLRL–50482), November 1968

CONTAINMENT OF RADIOACTIVE EFFLUENT

Clean Air Hearings, Senate Public Works Committee, June 24 to July 2, 1964

Isotopes Inc., Movement of Gaseous Radionuclides through Geologic Media, NVO–1229–85

GROUNDWATER CONTAMINATION AND MOVEMENT

Proceedings of the Third Plowshare Symposia (1964), Engineering with Nuclear Explosives, TID–7695

Holly, Donald E. and Fenske, Paul R. (1966), Transport of Dissolved Chemical Contaminants in Groundwater Systems, Geological Society America Memoir 110

Bear, J., D. Zaslavsky, S. Irmay (1968), Hydrodynamic Dispersion, Chapter 11 in Physical Principles of Water Percolation and Seepage. S. Irmay, Editor, Arid Zone Research, UNESCO, Pages 307–349

Lynch, E., C. Cullimore (1964), Special Distribution of Radioactive Materials Around the Cavity of an Underground Nuclear Detonation; HNS–47, AEC Contract AT(29–2)–12–29, Hazleton Nuclear Science Corporation

Lynch, E., S. Davis, G. Postle (1965), Transport of Radionuclide by Groundwater: Some Theoretical Aspects; HNS–1229–61, AEC Contract AT (29–2)–12–29, Hazleton Nuclear Science Corporation

Sharp, J., B. Sorenson, K. Geringer (1967), Groundwater Safety Monitoring, NTS; NVO–1229–96, AEC Contract AT(29–2)–12–29, Isotopes Inc., Teledyne

GROUND MOTION

Richter, C. F. (1958), Elementary Seismology

John A. Blume Reports Published as: NVO–99–12, –15, –20, –27, –29, –30, –31, and –35

Housner, G. W., Behavior of Structures During Earthquakes, Journal, Engineering Mechanics Division, American Society of Civil Engineers, Vol. 85, October 1959

Newmark, N. M., A Method of Computation for Structural Dynamics, American Society of Civil Engineers, Vol. 85, July 1959

Clough, R. W., Dynamic Effects of Earthquakes, Journal, Structural Division, American Society of Civil Engineers, Vol. 86, April 1960

Environmental Research Corporation, A Summary of Ground Motion Production—Procedures and Equations, NVO–1163–49

TSUNAMIS

Tsunamis, W. G. VanDorn in Advances in Hydroscience, Vol. 2, 1966

Tsunamis in International Dictionary of Geophysics, S. Runcorn (Ed.)

Proceedings of the Tsunami Meetings Associated with the 10th Pacific Science Congress, D.C. Cos (Ed.), IUGG Monograph #24, 1963

Menard, H. W., Marine Geology of the Pacific

GPO 874-392